GEOTHERMAL ENERGY PRODUCTION FROM HOT DRY ROCK: OPERATIONAL TESTING AT THE FENTON HILL, NEW MEXICO HDR TEST FACILITY

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ABSTRACT

The development of the technology to extract useful energy from rock at depth which is hot but essentially dry has been underway for about 20 years. The process of mining the heat from hot dry rock (HDR) entails pumping water under high pressure down an injection well into a geothermal reservoir artificially created in hot rock. The water traverses the reservoir, becoming heated by the rock as it does so. Upon reaching a production well, the water returns to the surface where its useful thermal energy is extracted. It is then recirculated to mine more heat. In this closed-loop system, the sole motive force is a high-pressure pump located directly upstream from the injection wellhead.

During 1992-1993, an extended operational testing program was conducted at the Fenton Hill, NM Hot Dry Rock (HDR) test facility. Approximately 6.3 l/s (100 gpm) of water was circulated for a total period of about 8 months through an artificial geothermal reservoir located about 3.5 km (11,500 ft) below the surface. Hot water was continuously returned to the surface at temperatures of 180-190°C (355-375°F). Under steady-state operating conditions, the temperature of the fluid produced from the reservoir showed no measurable decline over the span of the testing. In fact, tracer evidence indicated that access to hot rock increased as flow was directed preferentially to longer and longer pathways through the reservoir as the testing proceeded. The amount of water lost in passing through the underground reservoir also declined with time, eventually reaching levels of only about 7% of the injected volume.

Operating performance data verified that significantly more energy was produced than was required to run the test facility. Geochemical measurements indicated persistently low levels of dissolved solids and gases in the circulating fluid. Because the entire system was pressurized, nothing except waste heat was released to the atmosphere during the closed-loop testing.

The test program provided new information with regard to thermal, hydraulic, operational and environmental issues concerned with the development of HDR geothermal energy plants. The data gathered in this test will form the basis for the development of facilities to produce and market energy from HDR on a commercial scale. This paper reviews the results of the recent HDR flow testing program in detail and discusses the next steps required to move HDR technology toward full commercial application as an economic process for producing clean energy.

INTRODUCTION

A vast amount of thermal energy lies trapped within the earth at depths that can be reached with current drilling technology. To date, this geothermal energy resource has been brought to the surface and applied to practical uses only in those limited regions where hot natural fluids have been found. At present, these hydrothermal steam and hot water resources are applied to a wide variety of direct heating applications around the world. Electricity production from hydrothermal energy is more limited, but more than 2,700 MW of electric generation capacity based on hydrothermal resources has been installed in the western United States since 1960 (McClarty and Reed 1992). In fact, about 6% of the electricity consumed in the state of California is generated from these geothermal energy sources.

By far the largest fraction of geothermal resources exists in the form of hot rock that is not in contact with mobile fluid. The energy content of hot dry rock (HDR) at accessible depths has been estimated to be on the order of 10 million quads (a quad = 10^{15} BTU or approximately 180 million barrels of oil) (Armstead and Tester 1987). While HDR is abundant and widely distributed, until recently no method existed to retrieve and use this vast resource. For the past 20 years, however, the Los Alamos National Laboratory has been developing the technology to extract heat from HDR. More recently, a number of other countries including Japan, The United Kingdom, Germany and France have begun to investigate the feasibility of utilizing the heat mining techniques conceived at Los Alamos to recover HDR energy (Duchane 1991).

THE HDR HEAT MINING PROCESS

All the HDR development efforts now underway are based on the concept disclosed in a patent issued to the Los Alamos National Laboratory in 1974 (Potter et al.). The process involves drilling a well deep enough to reach hot rock and pumping water down the well under high enough pressure to open up natural joints in the rock. The pressurized water flows through these opened joints and is rapidly heated to a high temperature by contact with the hot rock. In this manner, an artificial geothermal reservoir consisting of a relatively small amount of water dispersed in a large volume of hot rock is created.

One or more additional wells can then be drilled into the reservoir at some distance from the first to tap this pressurized hot water and bring it to the surface for practical use. After its thermal energy has been extracted, the same water can be recirculated through the hot rock. When carried out as a closed-loop continuous process, HDR heat mining should have almost no environmental effects since only heat is permanently removed from the earth.

Heat mining has been demonstrated several times during the past decade. Flow tests of HDR reservoirs have been successfully completed in the United States, England, and Japan (Dash et al. 1981; Parker 1989; Yamaguchi et al 1992). In addition, extensive supporting scientific work has been carried out to enhance the understanding of factors involved in the creation and operation of HDR reservoirs. A large body of reservoir engineering, seismic, tracer, and geochemical information describing the characteristics of HDR geothermal systems has been developed and a number of economic studies have been carried out to assess the potential economic viability of constructing and operating HDR energy production facilities. An overview of these aspects of HDR technology was presented at the Emerging Energy Technology Symposium in 1992 (Gollahalli 1992).

In spite of the significant technical advances of nearly two decades, experimental progress toward demonstrating the practicality of operating an HDR energy extraction facility has been achieved only in the past two years as part of a long-term flow testing program at the Fenton Hill, NM HDR Test Facility operated by the Los Alamos National Laboratory for the United States Department of Energy. By late 1991, the Fenton Hill HDR reservoir (the world's largest, deepest, and hottest, HDR reservoir) had been coupled to a surface plant built to power-industry standards, making it possible to evaluate the operation of an HDR geothermal reservoir under steady-state conditions such as those which might be employed in the routine operation of a commercial electric power production facility.

THE FENTON HILL HDR TEST FACILITY

Fenton Hill is a flat-topped mesa in the Jemez Mountains of northern New Mexico located just outside the southwestern edge of the Valles Caldera, a silicic volcanic complex in northern New Mexico. The HDR site is situated at a point on the mesa which is adjacent to an all-weather road and utility lines. Because it had been burned over a few years prior to the start of the HDR Program, construction at the site could be undertaken with minimal environmental impact. The land is owned by the U. S. Forest Service and about 20 acres is occupied by the HDR Program under a special use permit. (Smith 1983).

Geology of the Fenton Hill Site: The Valles Caldera is the culmination of the evolution of the Jemez Moutains volcanic field. Features such as rhyolitic domes, flows and pyroclastics that are as young as 50 thousand years, and some hydrothermal resources, are found within the caldera itself. Measurements in shallow holes have indicated high heat flow in the region. At Fenton Hill, Cenozoic volcanics and sediments, and Paleozoic sediments, with a total thickness of about 0.73 km overlay a Precambrian granodiorite basement rock (Goff and Decker 1983) The basement rock is extremely impermeable, with a measured porosity in the range of only about 10^2 nanodarcies (Brown and Fehler 1989). The HDR site is outside the caldera itself and is therefore free of young and tectonically active faults.

The Reservoir: Figure 1 is a schematic representation of the underground and surface portions of the Fenton Hill HDR facility.

INSERT FIGURE 1

The HDR reservoir is centered in the Precambrian rock about 3.5 km below the surface Seismic, hydraulic, tracer, and simple geometric evidence indicates that the reservoir has a volume of about 16-20 million cubic meters and is ellipsoidal in shape, with axes ratios of approximately 3, 2, 1, respectively (Brown 1991; Winchester 1993). The longest axis tends north-south while the shortest axis lies in an approximately east-west direction, and the intermediate axis is tilted approximately 30° from the vertical. The fluid-carrying fractures are believed to be planar in nature with openings of a millimeter or less, although it has not been possible to identify the location, extent, and dimensions of specific fractures. The expansion of the fluid volume within the reservoir region is compensated for by the elastic compression of the reservoir rock. The reservoir is penetrated by two wellbores, each of which terminates in an open-hole zone approximately 300 meters in length. The distance between the two wellbores at the open-hole depth averages 100-150 meters.

The Surface Plant: The heart of the surface plant is the injection pump which supplies the motive force for moving the fluid through the circulation loop. Originally, two diesel-fuel powered reciprocating injection pumps were installed in the system. These were designed for use on an alternating schedule, with one pump in operation and the other in reserve at any point in time. The pumps could be adjusted for operation over a wide range of pressures and flow rates. Each was capable of injecting a maximum volume of about 10.7 l/s (170 gpm) of water at pressures as high as 34.5 MPa (5000 psi). For reasons unrelated to HDR technology, both these pumps failed within a span of two days during a period of normal operations. Several months of intermittent operations passed before a replacement centrifugal pump powered by electricity was installed in the system. While lacking operational flexibility, the electric pump was extremely simple and very reliable.

The injection pump, piping to the injection wellhead, both wellheads, the wellbores and all flow paths through the reservoir constitute the high pressure portion of the circulation loop. This part of the system has been built for operation at applied surface pressures of up to 34.5 MPa. The remainder of the loop, the low pressure side, includes a particle/gas separator, an air cooled heat exchanger, a makeup water pump, and connecting piping. This part of the system is capable of operation at up to 6.9 MPa (1,000 psi). It feeds directly back to the injection pump. The plant is designed for automated operation and instrumented for measurement of fluid temperature, flow, and pressure at numerous points in the loop (Ponden 1992).

THE LONG-TERM FLOW TEST PROGRAM

The goal of the long-term flow test (LTFT) program at Fenton Hill was to demonstrate that HDR reservoirs could be operated on a continuous basis to produce useful amounts of energy over an extended period of time. In the process of conducting this test, answers were sought to questions involving the expected thermal lifetime of this HDR reservoir, water consumption, operating and maintenance costs, and the geophysical, geochemical and environmental effects of long-term operation of an HDR system.

As a result of intensive discussions with the HDR Program Industrial Advisory Group, the LTFT was designed to simulate as closely as possible the conditions under which a commercial HDR power plant might operate. The pressure under which water was pumped into the injection wellbore was adjusted to the highest level that could be maintained without leading to expansion of the reservoir volume, as indicated by the onset of microseismic events and an increased rate of water consumption. Experience had shown that for the Fenton Hill reservoir this pressure was just under 27.6 MPa (4,000 psi).

A pressure of 9.7 MPa (1400 psi) was typically maintained on the production wellhead in order to prop open, by means of this imposed backpressure, the fluid carrying joints in the relatively low pressure region of the reservoir immediately adjacent to the outlet into the production wellbore. The system pressure was reduced to about 4.8 MPa (700 psi) at the outlet of the production wellhead and this pressure was maintained until the water was returned to the injection pump for repressurization and reinjection into the reservoir. The plant was computer-controlled, with fluid circulation maintained continuously, on a 24-hour-a-day basis under these constant operating conditions. For much of the test period, the facility was manned only during the daylight hours. On a number of occasions, usually as a result of power failures caused by local weather conditions, the plant went into an automatic shutdown mode.

Important system parameters such as pressure, temperature, and flow rate were monitored continuously. Measurements of the geochemistry of the circulating fluid were made several times a week. Finally, diagnostic procedures such as production-well temperature logging and tracer analyses were implemented every few weeks or at critical junctures in the test program.

Continuous operation of the Fenton Hill HDR plant began on April 8, 1992 and continued with only minor interruptions for 112 days. Catastrophic failures of both reciprocal injection pumps within a two-day period forced suspension of testing on July 31. Although the pump failures were not related to HDR technology, the ensuing lapse in testing while suitable replacement pumping capacity was being evaluated, procured, and installed, was a serious setback to the LTFT effort. By mid-February 1993, a replacement pump was in place at Fenton Hill and a second continuous phase of flow testing was begun. The new pump was a leased centrifugal unit powered by electricity. Once the appropriate modifications to the electric power supply at the site had been implemented, it proved to be highly reliable. The second continuous test period ran for 55 days until mid-April 1993, when the available funding was exhausted. Typical operating parameters during the two steady-state test phases are summarized in Table 1.

RESULTS OF LONG-TERM FLOW TESTING

Important new information was generated during the LTFT in regard to a number of important aspects of HDR technology. The most significant findings are discussed individually below:

Thermal Performance: As indicated in Table 1, below, there was no net decline in the temperature of the produced fluid over the course of the test program. Figure 2 is a comparison of temperature logs on several dates during the LTFT.

The data from these logs verify that the temperature of water issuing from the top of the reservoir zone was essentially constant from the beginning to the end of the test. In fact, tracer evidence indicates that access to hot rock improved as circulation continued. Figure 3 shows the transit profile of tracer compounds through the reservoir on a number of occasions during the LTFT. The tracer response varied in a

TABLE 1. OPERATING PARAMETERS DURING THE TWO PHASES OF THE LTFT

Phase	One	Two
Measured Performance Period	July 21-29 1992	April 12-15 1993
Injection Conditions		
Flow Rate, l/s (gpm)	6.74 (107)	6.49 (103)
Pressure, MPa (psi)	27.3 (3960)	27.3 (3960)
Production Conditions		
Flow Rate, l/s (gpm)	5.65 (89.7)	5.70 (90.5)
Backpressure, MPa (psi)	9.7 (1400)	9.7 (1400)
Temperature, °C (°F)	183 (361)	184 (363)
Water Loss		
Rate, l/s (gpm)	0.79 (12.5)	0.46 (7.3)
Percent	11.7	7.0

Note: A small amount of injected water returned to the surface through a leak in the injection wellbore.

regular manner with the time of first appearance of the tracer at the production well becoming longer and the rate of tracer return becoming slower as testing progressed.

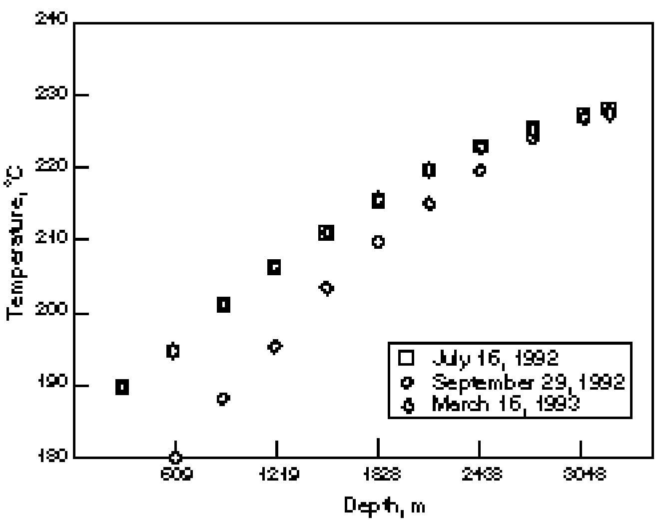

FIGURE 2. TEMPERATURE LOGS INDICATE THAT THE AVERAGE TEMPERATURE OF WATER ISSUING FROM THE FENTON HILL HDR RESERVOIR REMAINED ESSENTIALLY CONSTANT AT A DEPTH OF 3.18 KM (10,500 FT). THE TEMPERATURE DIFFERENCES BETWEEN THE LOGS AS THE WATER APPROACHES THE SURFACE REFLECT DIFFERENCES IN HEAT LOSSES TO THE REGION SURROUNDING THE WELLBORE RESULTING FROM VARIATIONS IN FLOW RATES.

Typically, when flowing water finds a short pathway between two points, it tends to enlarge and preferentially flow by that route. The development of such "short-circuits" has always been a concern in HDR reservoir engineering because the rock in contact with the short-circuit flowpaths would rapidly cool and the reservoir productivity would decline to the point that hot water would no longer be produced. These tracer results indicate quite the opposite effect took place in the Fenton Hill

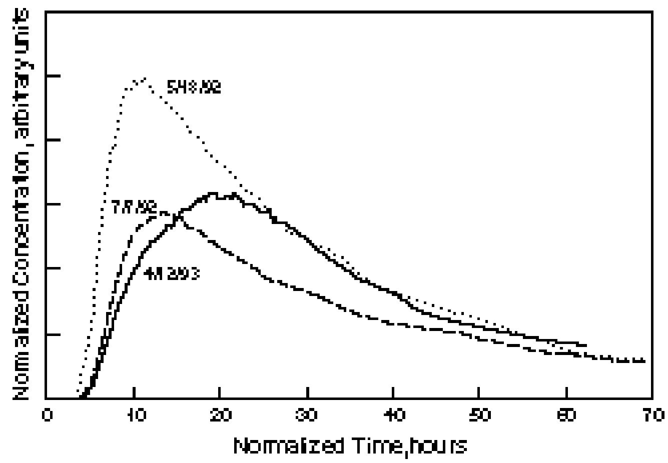

FIGURE 3. RECOVERY CURVES FROM TRACER EXPERIMENTS. THE CHANGES IN THE ONSET AND PATTERN OF TRACER RECOVERY INDICATE THAT THE CIRCULATING FLUID FOLLOWED LONGER, MORE CIRCUITOUS PATHWAYS THROUGH THE RESERVOIR AS TESTING PROGRESSED, IMPLYING INCREASING ACCESS TO THE HOT ROCK.

HDR reservoir during the LTFT, with pathways apparently closing as they cooled and new longer pathways, ostensibly in contact with fresh hot rock, developing. The tracer results bode well for the long term thermal stability of fluids produced from HDR reservoirs.

Water Consumption: Table 1 shows that water consumption averaged about 12% of the injected volume toward the end of the first continuous phase of the LTFT, but only 7% near the end of the second phase. Extrapolation of water loss trends from the beginning to the end of the LTFT (including the period of 7 1/2 months between the two steady-state phases of the test when the reservoir was continually pressurized but fluid circulation was intermittent) shows a long-term downward trend. This slow but steady decline in water consumption confirmed earlier static pressurization testing results which indicated that water losses decline as the microcrack fabric of the surrounding rock becomes pressurized (Brown 1991).

The amount of water that is lost to the subsurface in operating an HDR facility is a major concern, especially in those regions such as the American west where water resources are scarce. Apparent water losses arise both from permeation of water into rock beyond the boundaries of the artificial HDR reservoir and from diffusion into the microcracks of the reservoir rock itself. While the former phenomenon could be expected to continue indefinitely, but at a rate which may very slowly decline, the latter effect, as mentioned above, disappears as the reservoir rock becomes saturated at any given set of operating conditions.

Energy Production: The thermal energy extracted from HDR during the LTFT was measured and then released to the atmosphere through the heat exchanger. Thermal energy was produced at a rate of about 4 MW during steady-state operations. Table 2 relates the energy produced to the energy

TABLE 2.
ENERGY PRODUCTION TO CONSUMPTION RATIOS

	Operating Power Consumed	Thermal Power Produced	Potential Production of Electric Power 10% Conv.	15% Conv.
Phase 1 Diesel Powered Injection	1	6.4	–	
Phase 2 Electric Powered Injection	1	–	1.5	2.3

required to run the plant. During the first phase of testing, when diesel fuel was used to operate the injection pumps, the thermal output was more than 6 times the combined thermal energy content of the diesel fuel and the electricity used at the site.

The second phase of the test was an all-electric operation. Calculations indicate that if electricity had been generated during Phase 2 of the LTFT, about two-thirds of the electric production would have been required to operate the plant at a 10% thermal-to-electric conversion efficiency. At higher conversion efficiencies, of course, this parasitic power requirement would remain constant, so the ratio of produced to parasitic power would rapidly rise. It is important to note that until this test, all HDR experiments had been conducted with so many operational and experimental variables that quantification of net energy production was not possible. While the Fenton Hill HDR system was built as a research facility rather than for efficient energy production, its surface plant design permitted the kind of routine operation required to obtain this important data. Undoubtedly a plant constructed expressly to extract energy from HDR as efficiently as possible could produce much more output per unit input. A practical production plant, for example, would utilize several production wells strategically located to maximize energy extraction.

Environmental Effects: Under normal operating conditions there were no emissions to the atmosphere during the LTFT except waste heat. As shown in Table 3, dissolved gases in the circulating water remained at low and essentially constant concentrations throughout the test.

TABLE 3.
DISSOLVED GASES IN HDR PRODUCTION FLUID
(PARTS PER MILLION BY WEIGHT)

	April 15, 1992	March 15, 1993
Gas: Carbon Dioxide	2747	1830
Nitrogen	58	45
Oxygen	0.25	1.38
Hydrogen Sulfide	0.45	0.45

The only gas present in significant amounts was carbon dioxide. At the observed concentrations, the vapor pressures of all the gases were low enough so that they would remain in solution even at pressures well below the 4.8 MPa level maintained in the low pressure side of the circulation loop.

Maintenance Issues: Only small amounts of dissolved and suspended solids were picked up by the circulating water. Like the dissolved gas concentrations, the dissolved solids quickly reached essentially constant levels at low concentrations. Table 4 lists the type and concentration of dissolved species.

At about 4,000 ppm, the total dissolved solids content was extremely low compared to many hydrothermal fluids being commercially utilized, some of which have dissolved solids in excess of 300,000 ppm. The low levels of dissolved solids mean that scaling and corrosion should not be major problems in the operation of this HDR system. As a matter of fact, during twenty years of HDR experiments at Fenton Hill, corrosion and/or scaling of system piping and valves has never had an effect on normal operations.

THE NEXT STEPS IN HDR DEVELOPMENT

While limited in scope, the flow testing described in this paper has provided solid evidence of the potential of heat mining to provide clean and efficient energy, and has set the stage for the development of an HDR plant to produce and market electric power. The United States Department of Energy is currently soliciting industrial interest in a joint project to build and operate just such a facility. This pre-commercial HDR power plant will be designed from the start

TABLE 4.
DISSOLVED SOLIDS IN HDR PRODUCTION FLUID
(PARTS PER MILLION PER WEIGHT)

	Concentration in Production Fluid (parts per million by weight)	
Species:	April 15, 1992	March 15, 1993
Chloride	1220	1002
Sodium	1100	899
Bicarbonate	552	596
Silicate (as S_iO_2)	458	402
Sulfate	285	342
Potassium	95	91
Boron	47	34
Calcium	19	17
Lithium	19	15
Fluoride	14	13
Bromide	6.5	5.1
Arsenic	3.8	3.5
Iron	1.0	0.3
Aluminum	0.9	0.8
Ammonium	0.8	1.3
Strontium	0.8	0.8
Barium	0.2	0.2
Magnesium	0.2	0.2
Sulfide	0.2	0.9
Total Dissolved Solids	3845	3388

with operational efficiency in mind. A facility with a generating capacity of 1-25 MW is envisioned, small enough to keep the total capital commitment within reasonable bounds but large enough to benefit from the economies of scale. With government participation to help reduce the capital liability, and with engineering design aimed at significantly greater excess energy generation than could be achieved at Fenton Hill, it may be possible to operate a pre-commercial HDR power plant with a very favorable cost structure.

The joint industry/government venture will provide a means for documenting the capital costs involved in developing HDR resources for power production. If constructed at a site geographically and geologically different from Fenton Hill, the facility will also help demonstrate the practicality of utilizing HDR resources from a variety of settings. Perhaps, most important, the revenue generated in operation of the plant will provide the financial incentive to operate the plant for several years or even decades, thus building the kind of track record required to convince the harshest skeptics of the value of the technology.

SUMMARY

Efforts to identify, access, and recover the vast HDR geothermal resources of the world have been underway for more than 20 years. The basis for all current HDR energy programs is technology originally developed at the Los Alamos National Laboratory to circulate water through an artificial geothermal reservoir using a continuous, closed-loop process. Recently, a complete energy production facility consisting of a surface plant capable of sustained production connected to a large HDR reservoir was constructed for the first time at Fenton Hill, New Mexico. During the past two years, extended testing at Fenton Hill has demonstrated that energy can be extracted from HDR on a continuous basis. Thermal energy was produced continuously at a rate of about 4 MW in two test phases lasting 112 and 55 days, respectively, and intermittently for a period of 7 1/2 months between the continuous test segments. Temperature measurements at the surface and at depth indicated no decline in the average discharge temperature of water from the reservoir over the span of the test. In fact, tracer testing indicated that access of the circulating water to the hot reservoir rock improved as the test proceeded.

Other observations during the test were equally encouraging from the standpoint of the practicality of the technology: Water losses in circulation through the underground reservoir declined steadily throughout the test, reaching a level of only 7% of the injected volume by the time the test was terminated. Measurements showed that significantly more energy was extracted from the HDR reservoir than was required to operate the Fenton Hill circulation system and its supporting equipment. There were no atmospheric emissions during normal operations except waste heat. Dissolved gases and solids remained at low and essentially constant levels. Finally, with the exception of a major pump failure for reasons unrelated to HDR technology, the plant operated in a highly reliable manner.

The promising results of the recent LTFT Program have set the stage for the further development of HDR technology toward the point of commercial implementation. The United States Department of Energy is seeking industry participation in a joint venture to construct a facility to produce and market electricity generated from HDR energy. This pre-commercial plant would generate revenue for its operator and at the same time build the operating record required to convince the power industry that HDR can be a clean, practical and profitable energy resource for the 21st century..

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